NUSL White Paper: Dark Matter Experiments

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I. INTRODUCTION

Astrophysical measurements have progressed to the point that they now provide a reliable inventory of the contents of the universe. Measurements of the first acoustic peak in the angular power spectrum of the Cosmic Microwave Background (CMB) [1] indicate that the total energy density of the universe is near the critical density, $\Omega_{\rm tot} \equiv \rho/\rho_{\rm crit} = 1.0 \pm 0.04$, consistent with the prediction of inflation. Furthermore, separate measurements yield consistent results for the total densities of baryonic and non-baryonic matter, as well as for the amount of the so-called dark energy. The resulting "concordance model" calls for a dark energy density $\Omega_\Lambda = 0.67 \pm 0.06$, a total matter density $\Omega_{\rm M} = 0.33 \pm 0.035$, and a baryon density $\Omega_{\rm b} = 0.04 \pm 0.008$ [2]. The fact that stars and other measured, luminous matter account for only $\sim$1% of the total density means that most of the matter, even most of the baryonic matter, consists of unknown, dark components.

The best determination of the cosmological density of baryonic matter is from measurements of near-primordial deuterium in gas clouds towards distant quasars [3]. The theory of Big Bang nucleosynthesis accurately predicts the observed abundance of deuterium only if the baryon density $\Omega_{\rm b}h^2 = 0.020 \pm 0.001$ (where h is related to the Hubble constant by $H_0 \equiv 100h$ km^{-1} s^{-1} Mpc^{-1}). This value of the baryon density also leads to accurate predictions of the primordial abundances of the other lightest elements. The ratio of the amplitudes of odd to even acoustic peaks in the CMB anisotropy spectrum yields a result for the baryon density that is in stunning agreement: $\Omega_{\rm b}h^2 = 0.022^{+0.004}_{-0.003}$. This value is also indicated by (less constraining) measurements of the shape of the power spectrum of matter inhomogeneities [4] combined with measurements of the Hubble constant [5].

Several measurements give consistent results for the total cosmological matter density. CMB measurements, most notably the height of the first acoustic peak, constrain $\Omega_{\rm M}h^2 = 0.16 \pm 0.04$. Measurements of the shape of the power spectrum of matter inhomogeneities, as determined by large redshift surveys, constrain $\Omega_{\rm M}h = 0.20 \pm 0.03$. These results are in good agreement with those obtained by combining the measured baryon density with measurements of the baryon-to-total mass density ratio in clusters, as determined by X-ray measurements or by measurements of the Sunyaev-Zel'dovich distortion of the CMB. They are further strengthened by observations of distant supernovae [6], which indicate that $\Omega_\Lambda - \Omega_{\rm M} \approx 0.4$.

The fact that the measured matter density is significantly larger than the measured baryonic matter density indicates that most of the matter in the universe is non-baryonic particles outside the standard model of particle physics. An excellent candidate for non-baryonic particle dark matter is provided by supersymmetry, which is a well motivated extension to the standard model of particle physics. Although the energy scale where supersymmetry should appear is not *a priori* fixed, in order to solve the problem of mass hierarchies, *i.e.* the stability of the electroweak scale with respect to radiative corrections, the masses of the superpartners must be $\sim$1 TeV.

Several experimental hints favor such weak-scale supersymmetry. The gauge coupling strengths measured by accelerator experiments unify at the GUT scale if the masses of the supersymmetric particles are around 1 TeV [7]. Precision electroweak data favor a light Higgs boson [8], as predicted in the MSSM, the minimal supersymmetric extension to the standard model. Another hint for new physics at the TeV scale is provided by the new measurement of the anomalous magnetic momentum of the muon [9]. The measured 2.6σ deviation from the prediction of the standard model can be well explained by weak-scale supersymmetry [10, 11], which provides contributions to $a_\mu \equiv (g_\mu\text{-}2)/2$ via loops with supersymmetric particles.

In order to prevent baryon- and lepton-number violation in supersymmetric models, the conservation of the so-called R parity is imposed. The R parity takes the value +1 for all standard model particles and -1 for

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all supersymmetric partners. It implies that sparticles are always produced in pairs, that heavier sparticles decay into lighter ones, and that the lightest supersymmetric particle is stable. The stability of the lightest supersymmetric particle (LSP) renders it an excellent dark matter candidate. The LSP is certainly a neutral, weakly interacting particle, since strong or electromagnetically interacting particles would become bound in anomalous heavy isotopes, which are essentially ruled out by experiments.

A natural possibility for the LSP is the neutralino, a linear combination of the wino, bino, and the two higgsinos, which are the superpartners of the neutral gauge and Higgs bosons. If the neutralino is the LSP and hence is stable, it would be present today as a cosmological relic from the early universe. It would be an example of the general class of Weakly Interacting Massive Particles, or WIMPs [12], which were once in thermal equilibrium with the early universe, but were "cold," *i.e.* moving non-relativistically at the time of structure formation. The relic density of any WIMP depends on its annihilation cross section, with weak-scale interactions if the dark matter is mainly composed of WIMPs. More detailed calculations indicate that this general statement is accurate for the neutralino in particular: in a large class of supersymmetric models the abundance of the neutralino is high enough to account for a significant portion of the dark matter in the universe (*i.e.*, to yield a cosmological density between 0.1 and 0.3 of critical density).

For direct dark matter detection experiments, which search for the nuclear recoils produced in elastic scattering of neutralinos from nuclei, it is crucial to estimate the neutralino-nucleon cross section. This cross section, along with the density and velocity distribution of neutralinos in the vicinity of the solar system, determines the expected detection rates in a given detector.

There are many approaches in the literature to evaluate the neutralino-nucleon cross sections. In general, the considered supersymmetric models are classified according to the assumed mechanism for communication of supersymmetry breaking from the hidden to the visible sector. The most basic, yet well motivated approach is the minimal supergravity (mSUGRA) framework, which arises as a low-energy limit of a supergravity theory. In mSUGRA, supersymmetry is broken in the hidden sector of the model and transmitted to the observable sector via gravitational interactions, leading to soft SUSY-breaking masses at the TeV scale. At the GUT scale it leads to a universal scalar mass m_0, a universal gaugino mass $m_{1/2}$, and a common tri-linear coupling A_0. Models under mSUGRA are further characterized by the ratio of the vacuum expectation value of the Higgs duplets, $\tan\beta$, and by the sign of μ, the Higgs mixing parameter in the superpotential, meaning that all sparticle masses and couplings are derived in terms of the four parameters and one sign.

In general, it is found that in mSUGRA the spin-independent neutralino-nucleon cross sections lie between 10^{-6} pb and 10^{-11} pb, with the highest cross sections obtained for the smallest universal gaugino mass $m_{1/2}$ and for the largest $\tan\beta$.

More generic frameworks than mSUGRA are obtained by relaxing some of the unification and other theoretical assumptions. The most phenomenological minimal supersymmetry models define all the parameters directly at the weak scale and make no assumptions at the GUT scale. These models have a higher number of free parameters and in consequence are somewhat less predictive and testable. The general framework results in a wider range of possible neutralino-nucleon cross sections, often bordering or exceeding current limits.

Figure I shows the allowed region of parameter space including accelerator constraints on supersymmetry. As shown in the figure, current experiments are at best barely sensitive to some models. The experiments currently being built should be sensitive to much of supersymmetry parameter space. Significantly, if the measured 2.6σ deviation from the prediction of the standard model for the muon anomalous magnetic moment is due to supersymmetry, the neutralino mass must be $< 500\,\mathrm{GeV}$, and neutralino-nucleon cross section must be $> 2 \times 10^{-9}$ pb [11]. If the measurement is confirmed at a higher confidence level after more data is analyzed, then future dark matter projects presented in this white paper could be sensitive to the entire allowed parameter region.

II. THE EXPERIMENTS

Several 100-kg to ton-scale dark-matter experiments are in planning or proposal stages, with smaller-scale versions already running or currently under construction. Table I summarizes six such experiments. Some of these experiments are unlikely to be sited at NUSL; they are included nonetheless to give a wider sampling of possible types of experiments.

Many of these experiments allow rejection of the otherwise dominant electromagnetic background by determining whether the interacting particle produced an electron recoil or a nuclear recoil. Such discrimination is possible because the energy loss per unit track length is much higher for nuclear recoils than for electron recoils. Experiments may also be able to take advantage of the expected time dependence of a WIMP signal. If the number of detected WIMP events is large enough, and excellent stability of the experimental energy response, efficiencies, and backgrounds is maintained, it may be possible to detect a ~5% modulation in the WIMP

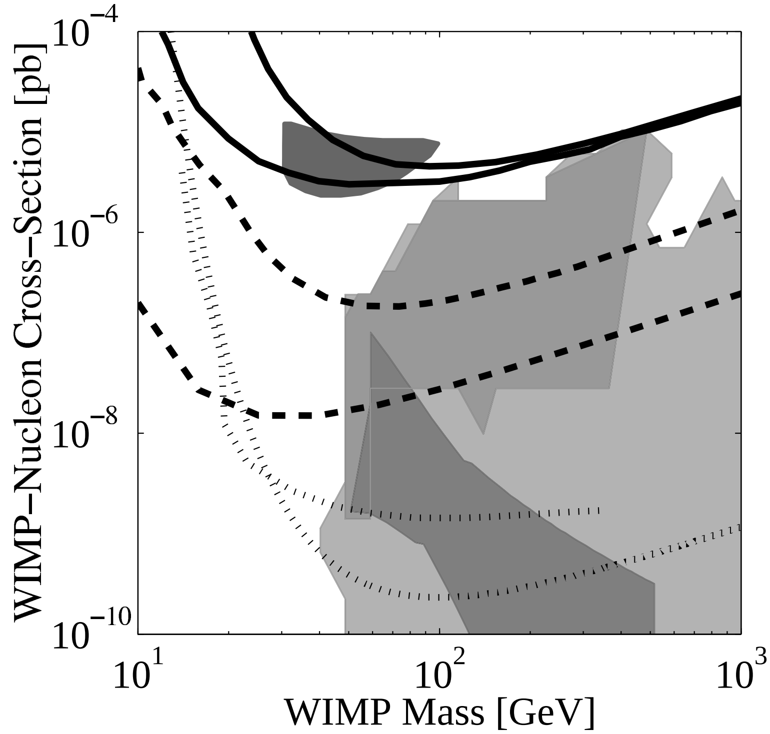

FIG. 1: Comparison of theoretical expectations and experimental sensitivities for direct detection of neutralino dark matter. Plotted are the neutralino–nucleon spin-independent cross section vs the neutralino mass. Solid lines (from top to bottom: EDELWEISS [13], CDMS I [14]) are current experimental limits. Dashed curves are projected sensitivities of experiments currently being built (from top to bottom: CRESST, CDMS II) Dotted curves are projected sensitivities of experiments described in this paper (from top to bottom: GENIUS, XENON). Solid region at upper left is the DAMA annual modulation region [15]. The remaining regions are theoretical expectations. Filling the entire lower right corner is the region allowed by the MSSM without the muon $g-2$ constraint [11]. Adding the muon $g-2$ constraint reduces the allowed region to its (darker) subsection in the upper left hand corner. The lower, yet darker region is consistent with the CMSSM [16]). Figure generated with the Dark Matter Plotter [17].

interaction rate and energy spectrum due to the Earth's orbit (*i.e.*, due to the change in the WIMP velocity distribution relative to the Earth over the course of a year). Detecting this annual modulation in a believed WIMP signal would help confirm the discovery, while a lack of annual modulation in the rate of events could improve an experiment's upper limits by indicating that most of the events detected are not due to WIMPs.

A. Ge diode experiments

Ge diode experiments, originally designed to search for the neutrinoless double beta decay in ^{76}Ge, were among the first to set limits on WIMP-nucleon cross sections [18, 19]. One of their advantages is excellent energy resolution (between 0.2 keV and 3 keV, depending on size and energy region) up to energies of a couple of MeV. Such resolution allows not only the achievement of energy thresholds as low as 2 keV ionization energy [20, 21] (8 keV recoil energy), but also the identification (and hence eventual elimination) of the main sources of radioactive backgrounds. Through stringent selections of detector components and by using specific shieldings against the natural radioactivity of the environment and against cosmic rays, Ge diode experiments have achieved the lowest absolute backgrounds measured so far [20, 22, 23].

1 The GENIUS proposal

The GENIUS project [24–26] plans to operate an array of 40-400 HPGe-detectors (100 kg-1 t) immersed directly in liquid nitrogen. The liquid nitrogen is stored in a tank 12 m in diameter and 12 m in height, surrounded by 2 m of isolating material (polystyrene foam). The isolation is held by an outer cylindrical vessel made of stainless steel. The Ge detectors are suspended in the center of the inner tank on a holder system made

	NR	Test Phase				Full Project	
Project Name	Disc.	Name	Mass	Location	Timescale	Mass	Timescale
GENIUS	No	GENIUS-TF	40 kg	Gran Sasso, It	2002-2005	100–1000 kg	2005-2015
MAJORANA	No	Phase 1,2	2–40 kg		2002-2007	500 kg	2007-2017
CryoArray	Yes	CDMS II	7 kg	Soudan mine, MN	2002-2006	1000 kg	2006-2017
ZEPLIN IV	Yes	ZEPLIN II	35 kg	Boulby mine, UK	2002-2007	1000 kg	2007-2017
XENON	Yes	Phase 1	7 kg		2002-2004	1000 kg	2004-2014
DRIFT 3	Yes	DRIFT 1,2	$\lesssim 1$ kg	Boulby mine, UK	2001-2005	100 kg	2004-2014

TABLE I: Summary of six proposed dark matter experiments, including estimates of the time scales for the full experiments and their smaller-scale versions. Four of the six experiments would use nuclear-recoil discrimination to help reduce the otherwise dominant electron-recoil backgrounds. Experiments without sites listed for their test phases could benefit from siting them at NUSL.

of low molecular polyethylene. Several concentric layers containing up to 37 detectors each are foreseen. The WIMPs are detected by measuring the ionization signal in the Ge crystals and by looking for the predicted annual variation in the event rate and energy spectrum. The aim of GENIUS is to reduce the absolute background of the Ge crystals by about three orders of magnitude with respect to current best measurements. This large step in background reduction would be achieved by removing almost all materials from the immediate vicinity of the detectors (crystal holder and cryostat system, which have been the main background sources so far) and operating the crystals directly in a cold liquid of extreme purity. The close arrangement of the Ge crystals in their support system would in addition provide a high amount of self-shielding.

Preliminary studies have shown that HPGe detectors work reliably under such conditions; low-energy thresholds (2.5 keV) and good energy resolutions (1 keV at 300 keV) were achieved with 300 g – 400 g crystals operated for up to three weeks in liquid nitrogen [25]. According to Monte Carlo simulations and background estimations, achieving a very low absolute background level is feasible with the thick liquid shielding if short activation times of the crystals at sea level (< 10 d) are ensured [25]. A critical point is avoiding surface contaminations on the inner (signal) contact of the Ge crystals (the outer surface of p-type detectors is protected by the ~ 300 μm n^+ "dead" layer).

The expected sensitivity of GENIUS for spin-independent WIMP nucleon cross section for an exposure of 100 kg y and a background level of 10^{-2} events/kg y keV is about 10^{-9} pb.

At present a small test version, GENIUS-TF [27], is under construction in the Gran Sasso Underground Laboratory. Fourteen natural Ge detectors (40 kg) will be operated in a volume of 0.064 m^3 of ultra-pure liquid nitrogen, the overall dimension of the experiment not exceeding 2 m$\times$2 m$\times$2 m. The primary goals of GENIUS-TF are to show that 'naked' Ge detectors work reliably in liquid nitrogen over a long period of time (at least for one year) and to test material selections for the various experimental components to sensitivities of 1 event/(kg y keV).

2 The MAJORANA Proposal

The primary purpose of MAJORANA [28] would be to search for neutrinoless double beta decay. However, it would also be sensitive as a WIMP detector. The experiment's basic concept is to operate multiple Ge diodes in one cryostat system in order to provide a high amount of self-shielding. A total of 210 enriched ^{76}Ge crystals in 10 21-crystal modules are planned. Each detector would be axially and azimuthally segmented in 2$\times$6 segments, allowing discrimination between single-scatter events, which are nearly always contained in one detector segment, and multiple-scatter events, which usually deposit energy in more than one segment. Two test phases are foreseen: the first one with one enriched ^{76}Ge crystal and the second with 14–18 enriched ^{76}Ge crystals in one cryostat system.

Although first test measurements and Monte Carlo simulations of the expected background in the low-energy region of the MAJORANA proposal are yet to be performed, preliminary estimates on the expected performance as a direct WIMP detection experiment can be made, based partially on experience with currently running Ge diode experiments.

The WIMP detection method is based on measuring the ionization signal in conventional, segmented Ge diodes. The background in the low-energy region is expected to be reduced with respect to existing Ge diode experiments due to high segmentation and close-packing of the Ge crystals [29]. Both effects will significantly reduce the Compton background of the Ge detectors and provide a handle against neutrons. Neutrons have a mean free path of several cm in Ge and thus will likely interact more than once. A large fraction of the neutrons are thus expected to be identified by their characteristic multiple-site interaction. Analysis of the pulse shape of the interactions could in addition provide event position information and thus help in eliminating events occurring at the surfaces of the detectors. This position information would offer a clear advantage, since surface contaminations of the crystals may be a limiting background for this type of dark matter experiment. Another expected advantage of segmented Ge detectors is a reduced capacitance and thus an energy threshold below 1 keV ionization energy.

The planned exposure of MAJORANA is 5000 kg years, allowing increased sensitivity by searching for the predicted annual modulation of the event rate and energy spectrum. This method requires a high detector stability over several years, stability which has already been achieved in Ge diode experiments consisting of far fewer crystals.

Assuming a flat background of 0.005 counts/(keV kg day) between threshold and 20 keV ionization energy, the expected sensitivity of MAJORANA for spin-independent WIMP nucleon cross sections via annual modulation analysis extends down to about 10^{-9} pb. Assumed are an energy threshold of 1 keV and a total exposure of 5000 kg years.

B. CryoArray

CryoArray [30, 31], using the same technology as the Cryogenic Dark Matter Search (CDMS), would use a large array of germanium and silicon detectors cryogenically cooled to ~25 mK. These detectors combine the ionization measurement of Ge diodes with a simultaneous measurement of the phonon energy produced in an interaction. These two measurements together allow rejection of electron-recoil background events. Cryogenic detectors share the excellent energy resolution of conventional Ge diodes. In CDMS I the resolution in the phonon and charge channels was $\lesssim 1$ keV. For events above 10 keV recoil energy, rejection of photons was > 99.95%, and rejection of low-energy surface electrons was > 95% [14]. The detectors of CryoArray are expected to have improved discrimination against surface electrons (> 99.5%) due to information on the interaction position from the phonon measurement. Comparison of phonon-pulse arrival times in a detector's four independent channels allows localization in the detector's xy-plane. More significantly, events occurring near detector surfaces result in phonon pulses with shorter rise times, allow their rejection. The inclusion of Si detectors, which are less sensitive to WIMPs than Ge detectors (see Figure 2), would help confirm that a possible signal is in fact due to WIMPs.

CDMS I, with ~ 0.3 kg active fiducial mass of Ge, ran at a shallow site on Stanford campus. CDMS II, which will have 42 detectors for a total mass ~7 kg, is currently being deployed at a depth of 2080 meters of water equivalent (mWE) in the Soudan mine and should run through 2006. For CryoArray, the detectors would be close-packed within a cryostat, with the full experiment likely consisting of several identical cryostats, each < 1 m^3. Simplifications over the current CDMS detector mounting should allow 10× the CDMS II detector mass to fit in the same cold space and ease materials screening. The challenge in constructing a 1-ton array at a reasonable cost will be to establish the necessary mass-production techniques for ~ 1000 detectors. The infrastructure built for CDMS II has led to the development of cold and warm electronics systems that already lend themselves well to mass production.

To reach its goal of sensitivity to 10 WIMP interactions per year, corresponding to a WIMP-nucleon cross section of 10^{-10} pb, CryoArray needs relatively modest improvements over CDMS, so long as the experiment is sited deep enough that the fast neutron background becomes negligible. The photon background needs to be reduced by $\sim 50\times$, through a combination of better materials screening and better self-shielding. The goal should be reachable; it is only 3× better than has already been achieved with Ge diodes. Potentially more difficult will be reducing the beta background by $\sim 300\times$. Better self-shielding will have an even greater impact for betas than for photons, but screening materials for low-energy surface betas will be a challenge.

C. Liquid Xenon experiments

Liquid Xenon has some excellent properties as a dark matter detector. First, it has a high density (3 g/cm^3) and high atomic number (Z=54, A=131.3). The high density allows experiments to be compact. The high mass of the Xe nucleus is favorable for WIMP scalar interactions provided that a low threshold energy can be achieved, as shown in Figure 2.

LXe is an intrinsic scintillator, having high scintillation ($\lambda = 170$ nm) and ionization yields because of its low ionization potential (12.13 eV). There are no long-lived radioactive Xe isotopes, and other impurities (like ^{85}Kr) can be reduced to a very low level by centrifugation or with a distillation tower and a cold trap. Krypton contamination levels as low as 1 ppb have already been achieved [32]. LXe is available in large quantities.

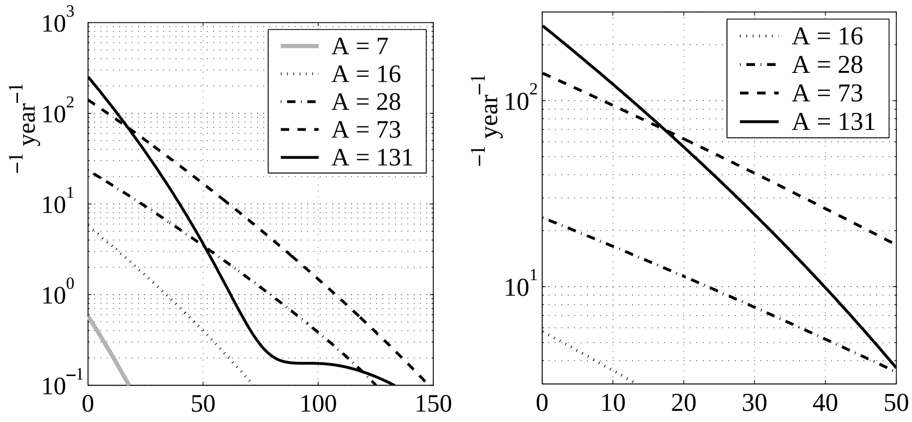

FIG. 2: Expected integral rates of WIMP interactions in Xe (A=131, dark solid), Ge (A=73, dashes), Si (A=28, dash-dots), S (A=16, dots), and Ne (A=7, grey solid) as a function of the recoil-energy threshold, for a 100-GeV WIMP with WIMP-nucleon cross section $\sigma = 10^{-9}$ pb, under standard assumptions of a dark matter halo. The small absolute rates expected set the minimum detector masses and maximum energy thresholds required to observe a signal. Decoherence of heavy nuclei reduces the advantage of heavy nuclei, particularly for large energies.

Scintillation in liquid Xe is produced by the formation of excimer states, which are bound states of ion-atom systems. If the electrons are drifted in a high electric field (10^5–10^6 V/cm), a secondary process, called proportional scintillation, can be detected. If the electrons are drifted out of the liquid into Xe gas, the secondary process is electroluminescence, which takes place at much lower fields of a few kV/cm. Measuring both the primary scintillation signal and a secondary process yields a method of discriminating between electron and nuclear recoils.

The elastic scattering of a WIMP produces a low-energy Xe recoil, which loses its energy through both ionization and scintillation. The number of fast scintillation photons is only about 25% of the number of electrons associated with an electron or gamma with the same energy [32]. The number of released free electrons is also small, due to the fact that the ionization electrons recombine very quickly. The strong recombination leads to the emission of more UV photons. Under a high electric field a nuclear recoil will thus yield a small charge signal and a much larger light signal, while for an electron recoil the opposite is true. The ratio of charge to light is thus at the basis of nuclear and electron recoil discrimination.

1 The ZEPLIN IV Proposal

The ZEPLIN IV project, with ZEPLIN II as prototype, is a proposal for a 1 ton two-phase (liquid and gas) Xenon detector [33]. The goal is to measure both scintillation and electroluminescent photons, allowing discrimination between electron and nuclear recoils. Experiments with a 1 kg LXe test chamber [34] have achieved thresholds lower than 10 keV recoil energy and factors of 1000 in discrimination.

Due to the high purity of LXe, the scintillation photons can be collected with a high efficiency and the electrons can be drifted to an anode region for readout. To maintain background discrimination at low energies, it is crucial to detect the few electrons produced in a nuclear-recoil event. The efficiency of this process is better in two-phase Xe than in the single phase. PMTs detect the primary scintillation photons a few nanoseconds after the event, while the electrons are drifted to the gas phase, where electroluminescence takes place. The same PMTs detect the electroluminescent photons after a few tens of μs, depending on the electron drift distance.

The prototype for ZEPLIN IV, ZEPLIN II, is under construction at UCLA and will be installed at the Boulby mine, UK. The fiducial volume of 35 kg of LXe is viewed by 7 PMTs placed above the gas phase. The static electric field to drift the free ionization electrons up to the gas phase is shaped by ten copper rings. Two wire frames form the electron extraction field at the liquid-gas phase surface and the electroluminescence field above the surface. The detector is vacuum-insulated with a double-layer chamber made of copper-cast vessels.

The plan is to design the one-ton version, ZEPLIN IV, after the same principle as ZEPLIN II. Eighty 5-inch PMTs will be placed above the liquid and gas phase systems, special attention being paid to reduce any dead regions in the detector. For a possible signal amplification, the insertion of an internal CsI photo-cathodes is being considered. The projected sensitivity of ZEPLIN IV is about $5{\times}10^{-9}$ pb for a raw background of 2 events/(kg d keV) and 360 days of exposure.

2 The XENON Proposal

XENON is a proposal for a modular liquid Xenon experiment with 10 time-projection chambers (TPCs), each containing 100 kg of active Xe target [32]. The target is self-shielded with an additional 150 kg of LXe, which provides a veto shield for background events generated in the containment vessel and other materials. XENON would be a two-phase Xenon experiment, detecting both primary and proportional scintillation signals. The electrons produced in a nuclear or electron recoil are drifted to the gas phase where they induce proportional scintillation light in a strong electric field.

The primary UV photons are detected by an array of PMTs placed above the liquid-gas interface. To increase the detection efficiency, a CsI photocathode is placed in the liquid and used to convert downwards-going photons into photoelectrons. To increase the primary light collection efficiency, the TPC walls are made of 90% Teflon which has a 90% diffuse reflectivity at 178 nm. Three signals are thus expected from one event: the prompt scintillation signal, the electroluminescence signal, and the proportional scintillation signal from the CsI photocathode. The difference in arrival time between the first two signals gives the z-coordinate of an event, while the x-y position can be determined by reconstructing the spot where the proportional scintillation pulse is produced. The 3D localization of an event permits background discrimination by fiducial volume cuts. Based on measuring these signals and on reconstructing the 3D position, the expected efficiency for background rejection is better than 99.5%, with visible energy thresholds of few keV, corresponding to recoil energies $\lesssim$ 10 keV.

The design of the LXe TPC would be the following [32]: a 30 cm high and 38 cm inner diameter cylinder, formed by a sandwich of Teflon spacers and thin copper rings for field shaping, contains the active LXe target. The cylinder is closed at the bottom by a thin Cu plate, the inside of which is coated with CsI. The top is closed by a larger Cu cylinder, housing the wire structure for the proportional scintillation field and 37 PMTs in a closely packed hexagonal pattern. The entire cylinder is enclosed in a copper vessel containing the LXe for active shielding. The scintillation light from the shield is detected by two rings of 16 PMTs. While the baseline detector concept is based on light read out with low-radioactivity PMTs, other readout schemes, based on large-area avalanche photodiodes or gas electron multipliers, are also under study.

The extrapolated sensitivity of XENON with 1 ton target material and 3 years of exposure is 4×10^{-10}pb. The assumptions are a background rate of 3.9×10^{-2} events/(t d keV) after 99.5% nuclear recoil discrimination and a visible energy threshold of 4 keV (corresponding to 10 keV recoil energy in LXe) [32]. Depending on the detector readout scheme and the efficiency of the self-shield, another factor of 4 improvement is expected.

A prototype with 7 kg of active material to test all design aspects and technical innovations, and demonstrate the high background-rejection efficiency and low energy threshold is foreseen.

D. DRIFT-3

The DRIFT (Directional Recoil Identification From Tracks) experiment [35] uses a negative-ion TPC. The negative ions are created by the slightly electronegative gas attaching to the electrons produced by a recoil track. Because negative ions diffuse much less than electrons do, no external magnet is needed to prevent diffusion, and sub-mm resolution is obtainable even after drifting the ions for meters. Measurements of the range of the recoil together with the total ionization caused should allow near-perfect rejection of background photons and electrons.

A cubic-meter prototype with 2-mm resolution and 250 g of CS_2 gas is currently running at a depth of 3000 mWE in the Boulby mine. A second-generation version with 0.5-mm resolution and increased pressure (and hence mass) is currently being proposed. DRIFT-3 would be a larger-scale version of the second-generation experiment, with 100 m^3 volume of gas at 160 torr, for a total active mass $\sim$ 100 kg. This relatively low mass, (compared to the other experiments described here) would likely limit the experiment's sensitivity to WIMP-nucleon cross-sections of 10^{-9} pb (corresponding to 10 event y^{-1}), depending somewhat on the Z of the gas ultimately used.

The primary advantage of the DRIFT experiment is that it should provide the directional axis of the recoil, and quite possibly the direction of the recoil as well. Because WIMPs should have a strong directional asymmetry in the frame of the Galaxy due to the movement of the sun around the Galaxy, this directional information can provide confirmation that a believed signal is due to WIMPs. The diurnal modulation due to the Earth's rotation results in $\sim$10% daily asymmetry, significantly larger than the size of an annual modulation, and less susceptible to possible systematic effects. Furthermore, this directional information could potentially be used to learn some information about the distribution of WIMPs in the Galaxy.

III. EXPECTED RADIOACTIVE BACKGROUNDS AT NUSL

A. Backgrounds from Natural Radioactivity

The rate of neutrons from natural radioactivity of materials near detectors can be made negligible through the careful choice of construction materials. Neutrons from natural radioactivity in the tunnel walls have a soft energy spectrum and so are well moderated by water or polyethylene shielding. Such shielding reduces the neutron flux by about an order of magnitude per 10 cm of material. Simulations indicate that 25 cm of polyethylene shielding reduce the natural-radioactivity neutron flux of 6×10^{-6} cm^{-2} sec^{-1} enough so that only ∼100 neutron interactions should occur per ton of target material per year. Using a total of 70 cm of such hydrogenous shielding should reduce the neutron flux by another ~ 4 orders of magnitude, resulting in a negigible detection rate.

The methods of reducing photon backgrounds varies a little from experiment to experiment. GENIUS cannot discriminate against backgrounds, so it uses a 12-m-diameter liquid-nitrogen shield. Majorana likely would also require significant shielding against external photons, despite its strong rejection of multiple-scatter events. Because the other experiments are expected to have excellent discrimination, ∼20 cm of lead should provide sufficient shielding (it would reduce the photon flux by over two orders of magnitude). It also may be cost-effective to line the cavern walls with low-radioactivity concrete or iron.

All the experiments need to minimize the radioactive contamination of the materials used near the detectors, and so would need access to a low-background counting facility to allow the screening of such materials. Screening against low-energy beta emitters would be particularly important for the CryoArray experiment because that experiment's intrinsic discrimination is worse for betas than it is for photons.

B. Cosmogenic Backgrounds

The required depth for the proposed dark matter projects is directly related to their expected cosmic-ray induced background. We will try to estimate the cosmogenic background rates due to muon-induced interactions, and, if data are available, to summarize the expected cosmogenic background due to exposure of detector materials above ground.

1 Cosmic-Ray Interactions at the Deep Site

Interactions of cosmic-ray muons at the deep site will produce photons and neutrons inside and outside the experimental shields. While external photons are prevented from reaching the detectors by passive or active shields, both internal photons and neutrons can be vetoed by a muon veto system. The most important, and possibly limiting background for direct dark matter detection experiments, are fast neutrons produced outside the detector shielding materials. These high-energy, 'punch-through' neutrons are difficult to tag with a veto system (active shields and veto systems deployed in the tunnel rock are under study [30]). After multiply scattering in the materials surrounding the detectors and reaching energies of a few MeV, these neutrons can produce the same signal in the detectors as a WIMP.

The muon flux at the Earth's surface is about 170 muons/(m^2 s), with an average energy $\langle E_\mu \rangle \approx 4$ GeV. At the NUSL site at 4500 meters water equivalent (mWE), this flux is reduced to about 800 muons/(m^2 yr), the muon spectrum being much harder with a mean energy $\langle E_\mu \rangle \approx 350$ GeV. Fast neutrons are produced in the rocks surrounding the experiments by one of the following processes: muon interactions with nuclei leading to nuclear disintegration, neutron emission by a nucleus following a muon capture, muon elastic scattering with bound neutrons, photo-nuclear interactions associated with electromagnetic showers generated by muons, and secondary neutron productions in these processes. The neutron yield as a function of the mean muon energy can be approximated by a power law $N \propto \langle E_\mu \rangle^{0.75}$ [36]. While there are many theoretical estimates of the energy spectrum of high-energy neutrons at deep sites, only few measurements exist. An empirical function which reproduces existing measurements fairly well has been found in [37], using the standalone FLUKA [38] Monte Carlo program.

In order to correctly estimate the expected background rate of each experiment due to high-energy (> 20 MeV) neutrons, detailed Monte Carlo simulations will be needed.

We will try to give a feeling on the expected high-energy neutron background by extrapolating from an example. The CDMS II experiment at the Soudan mine (2080 mWE) expects 8 nuclear recoil events due to external, high-energy neutrons, after an exposure of 6.8 kg yr (multiple scatters in the 42 detectors are not counted) [31]. A 1 ton Ge experiment would thus expect at most 1170 events/yr (the rejection efficiency for multiple scatters will depend on the granularity of each experiment) at the same depth. As a comparison, for a WIMP cross section of 10^{-10} pb, about 10 WIMP events/(t yr) are expected. Thus, even with a rejection efficiency of one order of magnitude due to multiple neutron scattering, the rate due to high-energy neutrons would still dominate over the expected WIMP rate at a 2000 mWE depth. At the 4500 mWE level of the NUSL site, the neutron flux is expected to be a factor of 25 lower than at Soudan. It would result in about 50 interactions due to high-energy neutrons per tonne and year. If an additional factor of ten reduction due to vetoing of multiple scatters can be assumed, the high-energy neutron induced background rate would be a factor of two lower than the expected WIMP rate at the 10^{-10} pb cross section. The deep NUSL site (6500 mWE) would offer an additional factor of about 50 reduction in the hard neutron flux. We believe that for the generation of experiments we are referring to in this white paper, the 4500 mWE NUSL site would provide sufficient shielding against the hard, cosmic-ray induced neutron spectrum, given the fact that all these experiments have a WIMP-nucleon cross section goal of about 10^{-9} pb.

2 Cosmogenic Activation of Detector Components at the Earth's Surface

During fabrication and transportation of detector components at the Earth's surface, high-energy, cosmic-ray-induced neutrons, protons, and muons can lead to the activation of these materials through spallation reactions. In order to calculate activation rates, the cosmic-ray spectrum and the cross sections for the production of the radioactive isotopes have to be known. The flux of cosmic-ray particles and its variation with geomagnetic latitude is well measured. However, the nuclear cross sections for the production of the isotopes are not so well known. Neutrons dominate (∼95%) nuclide production at the Earth's surface with protons ∼5% of the neutron rate. Muons also make a few % but are usually ignored. There are only few (n,x) and (p,x) cross sections measured as a function of the target mass and energy. Existing cosmogenic activation programs like SIGMA [39] and COSMO [41] use semiempirical formulas based on available experimental data in order to calculate the cross sections. The original formulas are given in [42], with more recent compilations in [43–45]. These programs use the compiled cosmic-ray intensities from [46–48].

In principle, calculations (or measurements) of the cosmogenics production in all WIMP target materials and possibly in the surrounding materials have to be performed in order to get an estimate of the allowed exposure at the Earth's surface and the required storage time below ground.

We discuss here cosmogenic production in Ge as an example, for in these cases extensive studies have already been performed [25], and moreover Ge is suggested by three of the proposals as a WIMP target material.

Table II shows cosmogenically produced isotopes in Ge for an exposure of 30 days at sea level and a subsequent storage below ground for 1 year. Only isotopes with half-lives longer than 200 days are shown. For ^{68}Ge the saturation activity is considered, since it cannot be removed during the zone melting process. The calculations were done with a modified [49] version of the COSMO program [41]. Limits on ^{68}Ge and ^{3}H activation from the CDMS-I 1999 data run are consistent with these calculations. The most troublesome radio-isotopes are ^{68}Ge and ^{3}H. ^{68}Ge is intrinsic and cannot be removed by the zone melting process. It decays by electron capture to ^{68}Ga, which emits a X-ray of 10.4 keV. ^{3}H decays by β^- decay with an endpoint energy of 18.6 keV.

To estimate expected count rates due to ^{68}Ge and ^{3}H, we take the two extreme cases of GENIUS, which measures only the charge signal and has a background goal of 0.01 events/(kg yr keV), and CryoArray, for which an electron-recoil rejection efficiency of 99.95% is assumed and the gamma background goal is 4.75 event/(kg yr keV). 2 μBq of ^{3}H would result in about 5 events/(kg y keV), which is already in the right order of magnitude for CryoArray and much too high for GENIUS. 172 μBq of ^{68}Ge result in about 2.5×10^3 events/(kg yr keV) in the 10.4 keV line. Although this is a much higher number, the decay of ^{68}Ge is less problematic, since the excellent energy resolution of Ge detectors at 10 keV will concentrate most of the events in few kev-bins around the line, and, moreover, ^{68}Ge will decay away after a few years of storage below ground.

Although achieving exposure times below 30 days at the Earth's surface certainly possible, and shielded production and transportation schemes are being discussed, the optimal scenario would be to produce the Ge detectors in a shielded facility directly at the NUSL site. This facility does not have to be at the same depth as the experiments themselves. A shallow depth of about 10–20 mWE would already be sufficient to eliminate the hadronic component of the cosmic-ray induced showers and thus to provide sufficient shielding to prevent activation.

A material used in most of the presented projects is copper. Table III lists the cosmogenically produced isotopes in Cu after an exposure of 90 days at the Earth's surface and an underground storage of one year. These values were calculated using the modified [49] COSMO [41] program. They should be used only as a reference. Each project will have to decide separately, based on Monte Carlo simulations of their specific setup,

Isotope	Decay	Half life	Energy deposition in Ge [keV]	Activity [μBq/kg]
^{3}H	β^-	12.33 yr	E_{max} = 18.6	2
^{49}V	EC	330 d	$E_{K(Ti)}$ = 5, no γ	1.6
^{54}Mn	EC, β^+	312.3 d	E_γ = 840.8, $E_{K(Cr)}$ = 5.4	0.95
^{55}Fe	EC	2.73 yr	$E_{K(Mn)}$ = 6, no γ	0.66
^{57}Co	EC	271.8 d	E_γ = 128.4, 142.8, $E_{K(Fe)}$ = 6.4	1.3
^{60}Co	β^-	5.27 yr	E_{max} = 318, E_γ = 1173.2, 1332.5	0.2
^{63}Ni	β^-	100.1 yr	E_{max} = 66.95, no γ	0.009
^{65}Zn	EC, β^+	244.3 d	E_γ = 1124.4, $E_{K(Cu)}$ = 9	9.2
^{68}Ge	EC	270.8 d	$E_{K(Ga)}$ = 10.37	172

TABLE II: Cosmogenically produced isotopes in Ge for an exposure of 30 days at sea level and a subsequent below ground storage of 1 year.

Isotope	Decay	Half life	Q-value [keV]	Activity [μBq/kg]
^{3}H	β^-	12.33 yr	18.6	6.3
^{22}Na	EC, β^+	2.6 yr	2842.2,E_γ =1274.5	0.7
^{49}V	EC	330 d	601.9	7.8
^{54}Mn	EC, β^+	312.3 d	1377.1, E_γ = 840.8	125
^{55}Fe	EC	2.73 yr	231.4	10.1
^{57}Co	EC	271.8 d	836, E_γ = 128.4, 142.8	28.5
^{60}Co	β^-	5.27 yr	318, E_γ = 1173.2, 1332.5	8.33
^{63}Ni	β^-	100.1 yr	66.95,	1.02
^{65}Zn	EC, β^+	244.3 d	1351.9, E_γ = 1124.4	123.8

TABLE III: Cosmogenically produced isotopes in Cu for an exposure of 90 days at sea level and a subsequent below ground storage of 1 year.

which of these decays are relevant and what maximum exposure and/or minimum deactivation times of the copper will be required.

IV. REQUIREMENTS FOR THE NATIONAL UNDERGROUND SCIENCE LABORATORY

The standard requirements of dark-matter experiments for the National Underground Science Laboratory are relatively simple. The required minimum room size to house the experiments varies greatly for the different experiments, from a mere 40 m^2 for the ZEPLIN experiment, to 10×50 m^2 for DRIFT-3. A single room to house several such experiments could potentially take advantage of common infrastructure such as a crane, water shielding, and a muon veto. The room(s) housing the experiments would need to be "cleanable," *i.e.*, able to be brought to clean-room standards during the initial assembly and possible later work on the experiment. During these times, the room air would need to be scrubbed to reduce radon levels; some experiments would require constant radon purging.

Experiments would need a modest (~ 50 m^2) room in the mine to house the data acquisition. Each experiment would require rooms with computer links at the surface, for offices, a control room (30 m^2) and a laboratory (30 m^2). Because stability during extended data-taking is critical, air conditioning would be necessary in the rooms housing both the experiment and the data acquisition. The power requirements are in general modest ($\lesssim 50$ kW).

Most or all experiments would need access to facilities at NUSL that could be shared with other rare-event search experiments. Each experiment would need use of a machine shop, under or above ground. As described above, a low-background counting facility, as well as a clean, radon-free storage area, would be needed. An additional clean room (of class 1000–10000) for staging and assembly of experiments (potentially at the surface), could also potentially be shared. While perhaps not necessary, nearly all of these experiments would benefit from an underground facility for electroforming copper; the Ge-based experiments would benefit from underground growth of the Ge crystals and detector manufacturing.

During installation, each experiment would likely require 5–10 people in the mine. Standard running would require only one or two people accessing the experimental areas. Periods of upgrades and run commissioning would require an intermediate number. The experimental areas should have 24-hour accessibility in case of emergency.

A. Additional Needs of Specific Experiments

Each experiment has additional requirements not covered in the previous section.

GENIUS:
GENIUS would require a room space of about 16 m in diameter and 19 m height in its conventional configuration with the liquid nitrogen tank above the ground level of the hall. A 2 t crane, a platform and a crown wheel would be needed to provide access to a class 100 clean room on top of the tank. The alternative layout would be to submerge the tank completely into the ground. This would require the excavation of a hole and coating it with water-proof concrete. The advantages would be multiple. The clean room would be at ground level, no extra platform and crown wheel would be required. The static design would be simpler and would provide maximum safety in case of a leak or an earthquake. In both cases, a liquid nitrogen filtering system based on active charcoal beds, as well as a nitrogen gas liquefaction system and liquid nitrogen supply would be required.

MAJORANA:
The phase 1 and 2 of MAJORANA would require a $4\times4\,\mathrm{m}^2$ footprint for the apparatus. Additional $3\times3\mathrm{m}^2$ for the counting house, as well as $2\times3\mathrm{m}^2$ for storage would be needed. In the third phase, the footprint of the apparatus would be $5\times4\,\mathrm{m}^2$. Additional $4\times4\,\mathrm{m}^2$ footprint for the staging and $4\times4\mathrm{m}^2$ footprint for the counting house would be required.

CryoArray:
CryoArray would require a main room $15\times5\,\mathrm{m}^2$, with 5 m height, with an additional room for cryostat pumps and plumbing ($25\,\mathrm{m}^2$), in addition to the standard room needs described above. A few He liquifiers, with $\sim$ 20 kW power consumption each, would be needed, as would storage of a few 100s liters of LN_2 and LHe.

ZEPLIN IV:
The required room space for ZEPLIN IV would be $5\,\mathrm{m} \times 8\,\mathrm{m} \times 4\,\mathrm{m}$ (height) with at least a 2-ton crane. Liquid nitrogen supply would be needed for safety reasons only.

XENON:
The laboratory space required by XENON would be $10\times30\ \mathrm{m}^2$. Electrical power of 100 kW, with 3-phase lines would be needed. The liquid nitrogen consumption is estimated to be about 3000 l/day. This would require an on-site big tank, with nitrogen lines to the underground lab, along with compressed air lines.

DRIFT:
DRIFT III could be configured for a room space of $10\times50\times6.5\,\mathrm{m}^3$ or $15\times15\times10\,\mathrm{m}^3$. A 5 t crane or bigger with minimum headspace would be required. The large gas TPC would require gas-handling equipment including exhaust treatment and safety ensurance.

V. CONCLUSIONS

Direct WIMP detection experiments are well motivated by the possibility that a large fraction of the dark matter in the Universe consists of a long-lived or stable, weakly interacting particle produced in the early Universe. The proposed experiments presented in this white paper would use a variety of techniques, from conventional Ge diodes, to liquid Xe scintillation detectors, Ge and Si phonon-mediated detectors and gaseous TPCs. In addition to measuring the recoil spectrum of the WIMP, all experiments could detect some sort of WIMP signature, either by comparing the spectral form and event rate in different type of materials, or by detecting the predicted seasonal or diurnal modulations due to the movement of the Sun and Earth around the galactic center. Some of the proposals already have smaller scale test phases located at other underground laboratories, while others would profit from the installation of a test phase at NUSL in the near future. The depth required by these projects would be the 4500 mWE level. All projects would benefit from a number of shared facilities, with relatively modest space and electrical power requirements.

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